A Flexible Polymer Tactile Sensor: Fabrication and Modular Expandability for Large Area Deployment

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***Abstract*—In this paper, we propose and demonstrate a modular expandable capacitive tactile sensor using polydimethylsiloxsane (PDMS) elastomer. A sensor module consists of 16 × 16 tactile cells with 1 mm spatial resolution, similar to that of human skin, and interconnection lines for expandability. The sensor has been fabricated by using five PDMS layers bonded together. In order to customize the sensitivity of a sensor, we cast PDMS by spin coating and cured it on a highly planarized stage for uniform thickness. The cell size is 600 × 600 μm^2 and initial capacitance of each cell is about 180 fF. Tactile response of a cell has been measured using a commercial force gauge having 1 mN resolution and a motorized z-axis precision stage with 100 nm resolution. The fabricated cell shows a sensitivity of 3%/mN within the full scale range of 40 mN (250 kPa). Four tactile modules have been successfully attached by using anisotropic conductive paste to demonstrate expandability of the proposed sensors. Various tactile images have been successfully captured by single sensor module as well as the expanded 32 × 32 array sensors. [2006-0035]**

***Index Terms*—Capacitive sensor, expandable scheme, flexible polymer, modular structure, tactile sensor.**

I. INTRODUCTION

RECENTLY, robot engineering has evolved to the level of implementing humanoids like Honda's ASIMO[1] or KAIST's Hubo,[2] and these robots are getting attention from people. iRobot's Roomba is already being deployed in daily life, although it is still in a primitive form.[3] As people start accepting assistant robots, there will be more robots permeating our lives in the near future than we ever imagined before. In order for these assistant robots to interact with humans safely and effectively, they must have various sensing capabilities. Some robots already have primitive vision and auditory sense. Along with these senses, the sense of touch will be inevitable for robots to make physical contact with humans and the environment to assist people. One of the effective ways to implement a sense of touch is to provide a robot a tactile sensor as an artificial skin.

In fact, various tactile sensors have already been introduced using diverse approaches for the last 30 years for various applications including minimally invasive surgery [1], [2].[4] Most of them are in the form of an array of distributed pressure sensors. In order for those tactile sensors to be successfully deployed in robots, it is desirable for them to have enough flexibility to cover a three-dimensional surface, compliance to absorb external impact and protect the sensor itself, adequate spatial resolution for dexterous manipulation of an object, reliable sensor response, and low crosstalk between tactile cells. They also should be able to be deployed in as large an area as required.

One approach is to use flexible and compressible conductive or dielectric sheets as a sensing material sandwiched by two other flexible layers with addressing conductive strips on them [3]–[10]. The conductive strips on flexible layers are placed in orthogonal direction, so that each crossing point forms a tactile cell in an array. The conductive or dielectric sheet is compressed by an external pressure inducing resistance or capacitance change in a cell. Some of those sensors took advantage of fabrics or rubber sheets for flexibility and large-area deployment over a palm size [3]–[6]. While these sensors can provide good flexibility in a large area, they do not have reliable response and show low spatial resolution of a few millimeters because precise control of dimension is difficult at submillimeter scale in their fabrication process. There are other sensors that use flexible polymer films, such as polyimide, as a structural material [7]–[9]. Since they are usually implemented by using more sophisticated fabrication technology such as screen printing, they show relatively good spatial resolution and reliable responses. However, they do not have enough flexibility to cover a three-dimensional surface. In addition, sensors using this approach are likely to have crosstalk between cells because isolation between cells is poor.

Another approach is silicon-based microelectromechanical systems (MEMS) tactile sensors [10]–[13]. These sensors have a diaphragm structure that deflects by external pressure. The deflection is typically measured by exploiting capacitance change between the diaphragm and the substrate [10] or by exploiting resistance change of strain gauges on the diaphragm [12], [13]. These sensors show reliable response, good sensitivity, high spatial resolution owing to the precision of semiconductor processes, and low crosstalk due to isolated cell structure enabled by MEMS processes. However, they are not flexible and their size is limited. Although a MEMS tactile sensor based on flexible polymer is reported recently, the size limit for large-area deployment still remains an issue [14].

The other approaches include optical [15], electromagnetic [16], or piezoelectric sensing schemes [17]. Optical tactile sensors typically have a bulky and complicated system structure,

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Color versions of Figs. 1 and 3–11 are available online at http://ieeexplore.ieee.org.

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[1] http://world.honda.com/ASIMO/

[2] http://ohzlab.kaist.ac.kr/

[3] http://www.irobot.com/

[4] http://www.pressureprofile.com; http://www.tekscan.com

which makes them expensive. An electromagnetic tactile sensor is also bulky, so that it is difficult to make an array. A piezoelectric tactile sensor shows hysteresis in response due to the characteristics of piezoelectric material.

To meet the requirements for tactile sensors, we introduced polydimethylsiloxsane (PDMS) elastomer as a structural material of tactile sensing for flexibility and compliance [18]. Since our sensor has isolated cell structures and is fabricated by using MEMS processes, it has low crosstalk, reliable response, and high spatial resolution. We also introduced a modular concept to our tactile sensor for large-area deployment, which has been quite difficult in many other MEMS tactile sensor approaches. In this paper, we present the concept, fabrication, and expandability scheme of our sensor in detail.

II. DESIGN

Fig. 1 illustrates the conceptual diagram of the proposed modular expandable tactile sensor and its operation principle. Each sensor module can be connected through interconnection lines to form an extended sensor skin for large-area deployment as shown in Fig. 1(a). One sensor module consists of a 16 × 16 cell array at the center and interconnection lines in the peripheries. The spatial resolution is 1 mm, which is similar to that of human skin [1]. There are three popular pressure sensing mechanisms for tactile sensors: resistive, piezoresistive, and capacitive sensing mechanisms. A resistive sensing mechanism measures resistance change induced from squeezed resistive material between electrodes [3], [5]–[9]. A piezoresistive sensing mechanism uses strain gauge to measure deformation of a tactile cell [11]–[15]. A capacitive sensing mechanism measures capacitance change induced from gap change between electrodes [4], [10], [18]. Among these mechanisms, we chose a capacitive sensing mechanism because it is less susceptible to noise and immune to temperature change. However, it is difficult to realize a cell structure that maximizes its sensitivity in a capacitive sensor array. For maximum sensitivity, a capacitive tactile cell has to have an air gap between electrodes. Air gap structure has been implemented by silicon tactile sensors since it is difficult to implement this structure with flexible material in a large area. In this paper, we develop a unique fabrication process to realize this air gap structure using flexible polymer for a large-area capacitive tactile sensor array. Fig. 1(b) shows the conceptual electrode structure of a capacitive tactile sensor and its operation principle. Upper and lower electrodes are crossing each other to form a capacitive array of tactile cells. A cell is composed of upper and lower electrodes and an air gap encapsulated by polymer structure. The air gap is squeezed with applied force to change the cell capacitance as shown in Fig. 1(b).

Fig. 2 shows the cross-section of the proposed tactile sensor cell and its dimensions. The cell is composed of five PDMS layers, and copper electrodes are embedded in the PDMS membrane. Two electrodes form a sensing capacitor between them, separated by total 12 μm (6 μm by a spacer and 6 μm by an insulation layer, respectively). The cell size and electrode size are 600×600 μm^2 and 400×400 μm^2, respectively. Initial capacitance of a single cell has been estimated as 171 fF, assuming the relative permittivity of PDMS as 2.75 given by product datasheet (Sylgard 184, Dow Corning). When pressure is applied to a bump, the upper PDMS deforms and capacitance increases until the air gap is completely closed. Therefore, the total thickness of the upper electrode and bump layer determines the sensitivity. Three types of cells with different upper PDMS thicknesses (470, 720, and 900 μm) have been tested in the work reported in this paper.

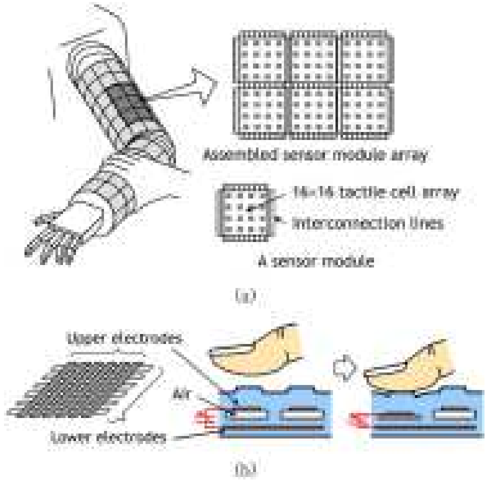

Fig. 1. Schematic diagram of the proposed modular expandable tactile sensor: (a) sensor module array and (b) structure of single tactile cell. The tactile cell capacitance changes as the air gap is squeezed according to applied force.

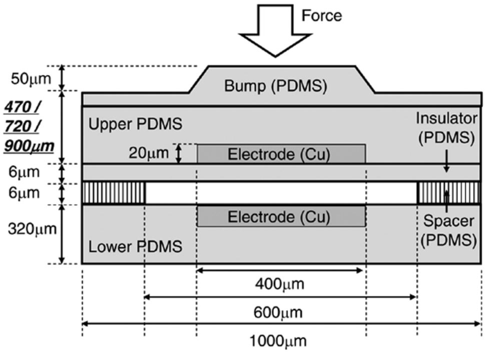

Fig. 2. Cross-sectional view of a tactile cell and its dimensions.

III. FABRICATION

In our design we use PDMS as a structural material; therefore, it is important to precisely control the thickness and uniformity of PDMS layers. We cast PDMS on a substrate by spin coating for reproducible thickness control and vulcanize it on a highly leveled stage for better uniformity. Fig. 3 shows the spin-coated PDMS thickness at various spin speeds and times. We could control the thickness of vulcanized PDMS from 21 to 300 μm by spin coating within ±7% variation. In order to make a PDMS layer with the thickness below 21 μm, PDMS solution should be diluted with n-Hexane. As for over 300 μm in thickness, it is difficult to control the PDMS thickness by spin coating. Fig. 4 illustrates the leveled stage for vulcanizing PDMS. Our target was ±5% uniformity for a 300 μm PDMS thickness over a 4-in wafer, but it is difficult to achieve that level of uniformity even by using a commercial laser leveler.

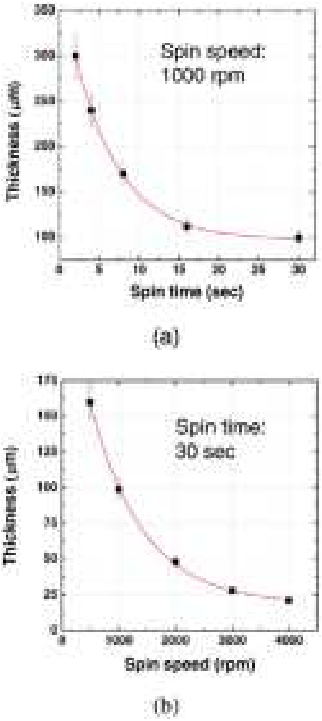

Fig. 3. Thickness of spin-coated PDMS layers for different spin speed and time: (a) with spin speed fixed at 1000 rpm and (b) with spin time fixed at 30 s.

Fig. 4. Highly planarized stage with a hot plate to improve PDMS uniformity: (a) schematic diagram and (b) its photograph.

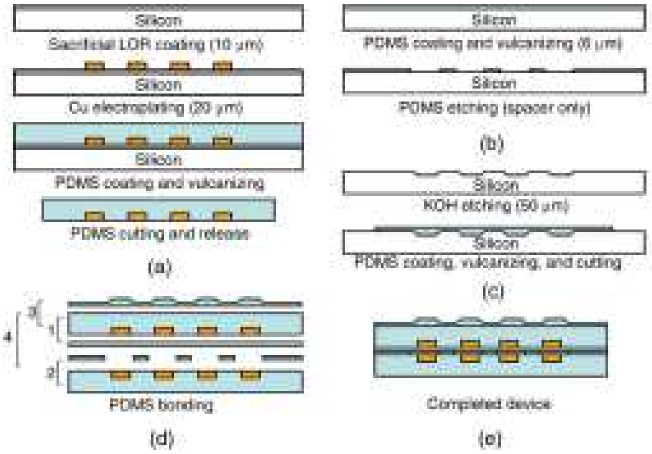

Fig. 5. Fabrication processes of the proposed tactile sensor module: (a) Electrode layer formation, (b) insulation and spacer layers, (c) bump layer process, (d) bonding sequence, and (e) the completed device.

Therefore, we set up our own planarized stage using self-leveling characteristics of liquid. As shown in Fig. 4(a), we made a container with aluminum foil and placed a stainless steel plate (30×30 cm^2) of 3 mm in thickness in the container on a hot plate. Then, we poured PDMS and vulcanized it at room temperature for two days. PDMS is self-leveled and forms a highly flat surface during vulcanization. In order to prevent wafers from being stuck to the PDMS in the stage, a transparent film is placed on the top of the planarized PDMS. Fig. 4(b) displays the leveled stage on a hot plate showing two wafers being planarized and vulcanized. We could achieve $\pm 3.5\%$ uniformity for 300 μm PDMS over a 4-in wafer using this setup. The thickness has been measured using a laser profiler from Keyence (VF-7500).

The fabrication process of each layer is shown in Fig. 5(a)–(c). Each layer is processed separately and bonded together after oxygen plasma treatment [19]. For the electrode layers [Fig. 5(a)], LOR 20B from Microchem is spin-coated about 10 μm on a silicon wafer. LOR is used as a sacrificial layer. Then, copper electrode (20 μm) is formed using electroplating. AZ9260 photoresist is used as an electroplating mold. Next, titanium is sputtered as an adhesion layer. After O_2 plasma treatment of the titanium surface for 8 min at 50 W, PDMS is spin-coated about 300 μm and cured on the leveled stage. PDMS should be cured at room temperature to prevent the layers from being deformed after release due to thermal expansion difference between the copper and PDMS layers. Thickness uniformity was controlled under $\pm 3.5\%$ over a 4-in wafer. After vulcanizing PDMS at room temperature, the electrode layer is cut and peeled off. The insulation and spacer layers [Fig. 5(b)] are formed by spin-coating of PDMS diluted with n-Hexane (Sylgard 184 A:B:n-Hexane = 10:1:10 in weight) on silicon wafers with sputtered platinum on them. Platinum has been used to weaken PDMS adhesion to the substrate for detachment which will be performed later. The thickness of both the insulation and spacer layers is 6 μm. The spin-coated PDMS is patterned and etched using reactive ion etching (RIE) for 45 min with 3:1 SF_6/O_2 gas at 100 mTorr to form a spacer layer. AZ4330 photoresist of 8 μm in thickness was used as a masking layer. It was reported that PDMS is etched well with 3:1 CF_4/O_2 gas in RIE before [20], but we used SF_6/O_2 and achieved a similar result. The PDMS etch rate is about 150 nm per minute. The bump layer [Fig. 5(c)] is fabricated using a silicon wafer etched in KOH as a mold. After platinum is sputtered on the mold, PDMS is spin-coated and cured.

The fabricated five layers are aligned and bonded together using a conventional contact aligner (Quintel Q-7000) with slight modification according to the sequence shown in Fig. 5(d) and (e). We used a transparent film as a carrier for the

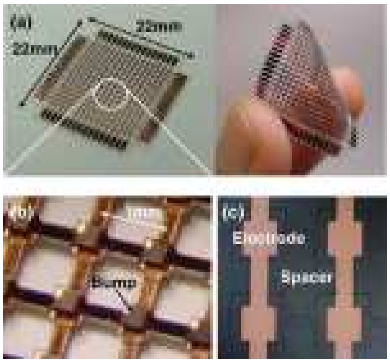

Fig. 6. (a) Fabricated tactile sensor module, (b) magnified view of cells, and (c) the bottom electrodes and spacer layer of four tactile cells.

Fig. 7. Measurement setup for single tactile cell characterization.

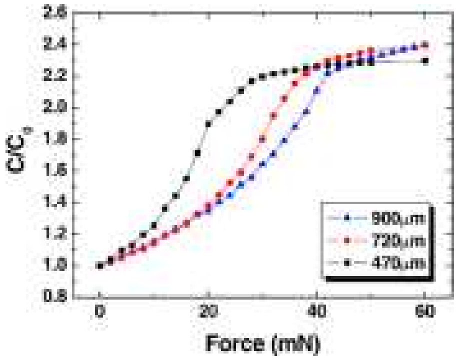

Fig. 8. Measured response of the fabricated tactile sensor cell with thickness variation of upper PDMS layers.

fabricated PDMS layers during cleaning, O_2 plasma treatment, and bonding, for it gives adequate stiffness for support and flexibility for peeloff of the PDMS layers. The total thickness of the cells is determined by bump layer thickness.

Fig. 6 shows the completed tactile sensor module. The size of one sensor module is $22 \times 22\ \mathrm{mm}^2$ including interconnection lines. The fabricated sensor shows good flexibility, as shown in Fig. 6(a). Fig. 6(b) shows the magnified view of four cells, and Fig. 6(c) shows the embedded electrodes with a bonded spacer layer. Air channels are formed to prevent the squeezed air from affecting the cell response. These air channels connect all the cell cavities to the atmosphere and maintain the pressure of each tactile cell cavity equal to the pressure of the atmosphere.

IV. MEASUREMENT RESULTS

We set up custom-made equipment for contact force characterization because there is no commercial tool available for contact force measurement in a small scale. Fig. 7 displays our setup for contact force measurement. A microforce gauge from AIKOH Engineering Co. has been used with a precision z-axis translation stage that has a 100 nm resolution. This gauge has 1 mN resolution and applies force with a sharp tip. Fig. 8 shows the measured response of the fabricated cells for various thicknesses of the upper PDMS layer. The y axis represents the ratio of the measured capacitance to its initial capacitance as a function of applied force. The initial capacitance of a cell has been measured as 180 fF. All the cells show saturation after 40 mN (250 kPa), which means both upper and bottom electrodes are in contact with the insulation layer between them. A cell becomes more sensitive as the upper PDMS layer thickness reduces. We have measured a sensitivity of 3%/mN for a 470-μm-thick membrane for small deflection.

Fig. 9 illustrates a schematic of the readout circuit to capture tactile images. For illustration simplicity, only a 3×3 cell array is shown for readout circuitry. First, one cell is selected by row and column decoders, and the reset signal is applied in order to reset the amplifier. Then, the selected capacitor (C_{pix}) is charged to V_{step}. When V_{step} is switched to the ground, the stored charge in the cell is transferred to the feedback capacitor (C_f) and generates an output voltage change as given in the equation in Fig. 9. In this research, we have implemented the circuit to read the cell capacitance within 100 μs, which implies 20 frames per second. The circuit reads a single cell twice with and without "reset" of the feedback capacitance (C_f in Fig. 9) to remove offsets from the circuit. For the initial capture of tactile images, we have used the off-the-shelf low-speed components for our interface printed circuit board. But if we would use the high-speed dedicated components with more than 10 MHz bandwidth, the maximum frame rate can be up to 1000 frames/s. A few tactile images captured from the fabricated sensor are shown in Fig. 10. Pressure has been applied by rubber stamps inscribed with alphabets, and their corresponding images can be captured clearly by the fabricated tactile sensor.

V. EXPANDABILITY

Expandability of the sensor module has been demonstrated by stitching four sensor modules, as shown in Fig. 11(a), by using anisotropic conductive paste (ACP), which is widely used in plasma display panel (PDP) or liquid crystal display (LCD) packaging. ACP is a kind of thermally curable epoxy adhesive including conductive balls. The density of balls is so low that the epoxy is an insulating film in its initial formation. However, once ACP is squeezed between two electrodes and cured, the electrodes are connected electrically through the squeezed balls. To cure ACP, pressure of about 0.4 MPa has been applied at 120 °C for 15 min as shown in Fig. 11(b). All interconnection lines were electrically connected without failure with contact resistance below 100 mΩ. Mechanical bonding strength is so strong that we could not detach two bonded modules without tearing them. Fig. 11(c) shows the tactile image of character

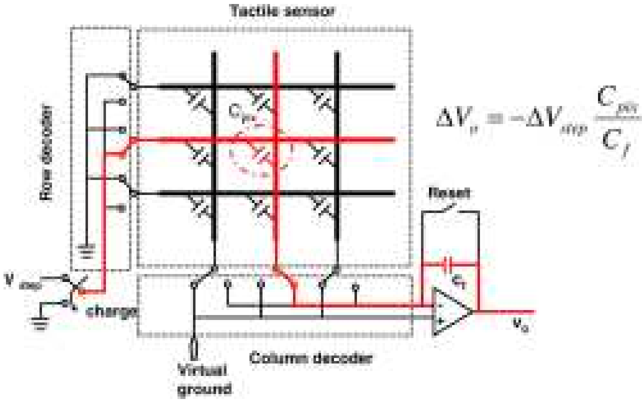

Fig. 9. Schematic of readout circuits for the fabricated sensor module.

Fig. 10. Flipped photographs of rubber stamps and their tactile images captured by the fabricated tactile sensor module.

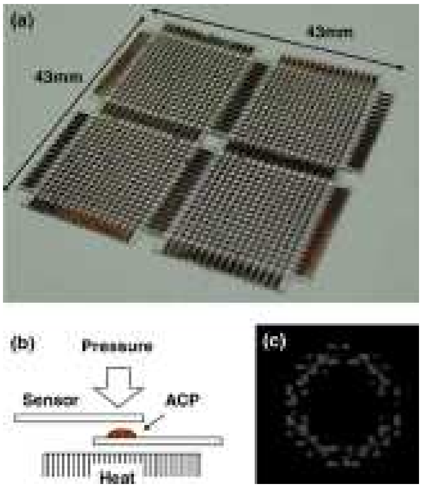

Fig. 11. (a) Expanded tactile sensor module in a 2 × 2 modular array, (b) module to module bonding by using ACP, and (c) measured tactile image of a character "O" using the 2 × 2 expanded sensor module forming a total 32 × 32 tactile cell array.

"O" captured by the expanded 2 × 2 sensor module array (or total 32 × 32 tactile cell array).

VI. CONCLUSIONS

In this paper, we have proposed and successfully demonstrated a new modular expandable tactile sensor using PDMS. A sensor module consists of a 16 × 16 tactile cell array with 1 mm spatial resolution. The thickness of PDMS has been controlled by spin-coating of PDMS. The uniformity of PDMS layers has been controlled less than ±3.5% at 300 μm thickness over a 4-in wafer using our custom planarized stage. The fabricated tactile sensor module shows good flexibility and captures distinctive tactile images. The expandability of the fabricated tactile sensor has been demonstrated successfully by stitching four modules using ACP to form a 32 × 32 expanded tactile sensor array. Since the proposed tactile sensor modules are flexible, robust, compliant, and easily expanded to a large area as needed, they can be a good candidate for deployment of robotic tactile skin applications in the future.

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